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# DETERMINATION OF CRACK GROWTH RATES FROM FRACTURE DATA IN RUBBERY PARTICULATE COMPOSITES

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## INTRODUCTION

During the last century two distinct branches of rocket propulsion technology emerged: solid rocket motors (SRM's) and liquid propellant systems. Both are useful for different applications. The solid rocket motor is the simpler and has been used to boost large payloads for long distances or high altitudes. The simplicity of the design lowers the probability of failure, however, the consequences of failure are large, so engineers are still trying to reduce risk using a combination of nondestructive inspection (NDI) and structural analysis. Cracks that emerge and grow during manufacturing, storage, and handling of the rocket are one cause of failure that we can control better with improved experimental approaches.

Any flaws detected with NDI are studied using fracture mechanics. The engineers try to calculate a relevant fracture parameter (such as the stress intensity factor) from the structural geometry and applied loads for comparison with laboratory determined toughness values. For this approach to be effective, we must perform both the structural analysis and the laboratory measurement and analysis accurately. Both initiation of crack growth and subsequent growth rates are important because cracks in propellant grow slower than in conventional materials. Sometimes the mission may be accomplished before a slow growing crack reaches a critical length. In other cases, the burning propellant surface may overtake the growing crack.

When fracture mechanics began its development, engineers were concerned mostly with brittle fracture, which is characterized by high-speed crack growth. The growth was both sudden and catastrophic, so that the measurement of conditions at the initiation of crack growth, rather than the subsequent growth rate was the dominant issue. In addition, for brittle materials nonlinear effects were small, so that well-defined cracks characterized the fractures and the crack tips had very small nonlinear near-tip regions.

The cracks in a solid rocket propellant material grow more slowly – enough to be measured and predicted. Even growing cracks in the actual structure can sometimes be innocuous. Because of the unusual nature of the material and of the application, using fracture mechanics in these instances involves some additional complications. First, the manufacturing process doesn't ensure material uniformity within any single material batch, so the properties may vary throughout a block of material (sometimes by up to 30%). Also, on a smaller scale the material is also heterogeneous, consisting of a high volume fraction (up to 60%) of hard particles embedded in a rubbery matrix. During crack growth, the crack changes speed and direction as it interacts with these particles. Finally, the rubbery matrix material can sustain large deformations (up to 30%), which results in good toughness, but creates additional difficulties. For example, analysis may have to incorporate nonlinear geometries, and the crack tip may blunt excessively, making its location somewhat subjective (see Fig. 1). All these

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issues influence the measurement and prediction of crack growth in the rubbery particulate composite (RPC); the most obvious effect is in the scatter of the crack growth data.



Figure 1: Tip of Crack Growing in a Rubbery Particulate Composite

The experimental method and data analysis also affect the crack growth determinations. Since we can control these items, we have tried to reduce data variability by optimizing our approaches in these areas. The work presented here is important because it summarizes the current state of the art in measurement and analysis of crack growth in RPC material; the information includes input from many members of the experimental community rather than a single researcher or research facility. As the field continues to evolve, the standardization of methods should enhance SRM reliability. Readers can use the information to design and construct experiments on RPC materials while avoiding some pitfalls.

## MEASUREMENT METHODS

The specimen geometries and test procedures affect the data variability and the feasibility of certain measurement procedures. Most of us who experiment on RPC materials use constant strain rate tests (i.e., constant crosshead displacement rates). [1–6] One possible reason for this is that the loads measured are small and the type of testing machine used most often for these load ranges is a screw-driven tensile testing machine. These machines easily apply constant crosshead speeds but require more instrumentation to apply constant load conditions. The strain rates used should simulate the structural conditions, which vary depending on the circumstance (e.g., low rates for thermal expansion/contraction in storage conditions and high rates for pressurized conditions).

Another feature common to many test procedures is the use of thin specimens. With thin specimens, researchers are confident that their surface-based measurements represent the actual crack size through the entire specimen thickness. Other very thick specimen geometries have been used in the past, with the most common reason being the need for constraint conditions similar to the actual structure.

Some of these specimen geometries were actually subscale motor geometries. Besides subscale motors, another frequent way to measure the crack growth while addressing the constraint issue is to use the *biaxial test specimen*(see Fig. 2). This was the most commonly used test specimen. [3,5] The placement of the crack at the center of a very wide specimen helps ensure that biaxial conditions are met, meaning that the normal stresses in the horizontal and vertical directions are about equal. This is the situation encountered by a crack aligned with either the longitudinal or circumferential axes in the SRM application.

Although this approach produces biaxial constraint conditions, the specimen also uses two crack tips, which can cause some complications. For example, small specimen misalignments can be manifested in the preferential growth of one crack tip over another. Also, experimenters must track the location of both crack tips during the entire process. [3,5]

2w = 203.2 mm
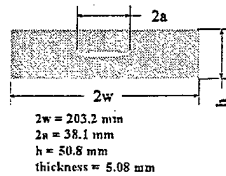2a = 38.1 mm
h = 50.8 mm
thickness = 5.08 mm

Figure 2: Typical Geometry for Biaxial Test Specimen

Because of this, single crack tip geometries have also been used extensively (for example, the *single edge notched tension specimen* shown in Fig. 3). The constraint conditions are not biaxial, but the single crack tip simplifies analysis. One additional complication is that due to the asymmetry of the cracked geometry, the specimen halves may pivot about a hinge point near the crack tip, causing excessive rotations that complicate later analysis. Sometimes we have installed special loading fixtures to help alleviate this problem (see Fig. 4). [6]



w = 25.4 mm
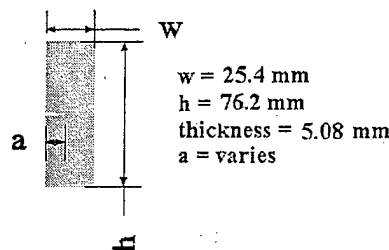h = 76.2 mm
thickness = 5.08 mm
a = varies

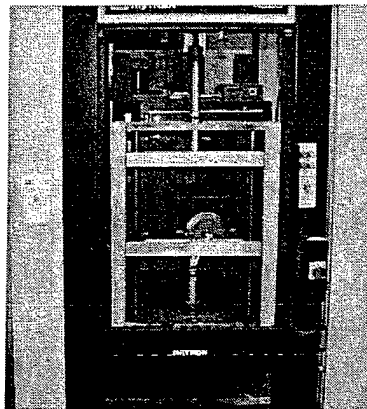Figure 3: Typical Geometry for Single Edge Notched Tension Specimen



Figure 4: Test Fixture Used to Prevent Specimen Rotations

By far the most common way to measure crack size is to measure the crack length on the specimen surface with videotape. [1–6] The measurements can be made after the experiment with either manual measurements made on a monitor screen or with software that downloads captured images (both methods are used). Some object or mark within the field of view of the camera must be used for a scale measurement (often this is the original crack size itself, or another specimen dimension). The advantages are the ease of use for slow to moderate crosshead speeds (e.g., up to 50.8 mm/min) and the lack of expensive equipment. The most common complaint was the time-consuming nature of data acquisition. Difficulties arise when the video camera field of view can't encompass the entire

crack, which is required for a length measurement, and when higher crosshead speeds are needed. Higher speeds can be accommodated with high-speed video equipment, although at a greater price). Engineers must synchronize the two sets of data (load vs. time from the testing machine and crack size vs. time from the videotape analysis) using some event that both systems can detect. For example, the fracture of the last ligament on the test specimen shows up on the videotape clearly and also in the test machine data, so this point can be used for synchronization. The times for this event on videotape are adjusted so that this matches the time recorded by the tensile testing equipment. Figure 5 shows a flowchart for the data acquisition process.
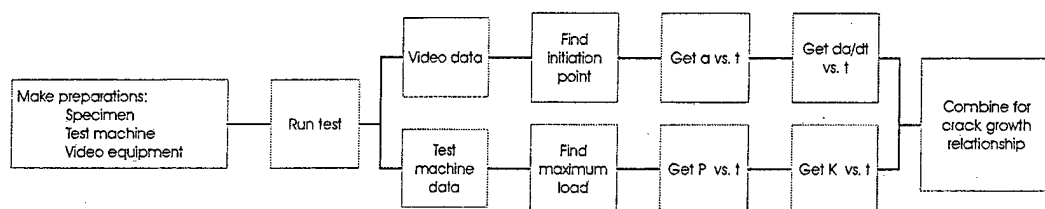


Figure 5: Flowchart of Data Acquisition Procedure

We have also used other measurement methods. As an aid to measurement, experimenters have attached to the specimen plastic sheets with grids on them (or have used grids printed on the specimen surface) so that the crack length could be measured by its location relative to the grid points. [4]. Also, when measuring growth in subscale motor specimens, the use of several colored dyes and the use of a ruled card inserted into the mouth of the crack were methods to establish crack size. These two methods are unique because they are both nonsurface measurements, although access to the crack mouth is required. This is not possible in some situations (for example in a pressure vessel) and limits the number of measurements that can be made, but is very useful in situations where the surface measurement cannot be easily taken. [2]

The strain rate of the test affects the test duration and largely determines the time interval for crack measurements. Engineering judgment is also used. In most cases, a constant time interval was used throughout each test. Work has been done in the past to determine the optimal time intervals that minimize error. [1]

## METHOD OF DETERMINING CRACK SPEED

Mostly researchers used crack size vs. time to determine crack speed and then related this to a crack tip parameter using a power law (see eq. 1 below). The most common crack tip parameter was the stress intensity factor, $K$, although $J$ has also been used. [1,3–6]

$$\frac{da}{dt} = CK^m \tag{1}$$

The crack growth rates are determined indirectly from the crack size vs. time data using different mathematical approximations, which influences the scatter in the data. The most commonly used method, for example, is the secant method, which is really a finite difference method for determining derivative approximations from two consecutive data points (see eq. 2). [1,3–5]

$$\left|\frac{da}{dt}\right|_{t=t_i} = \frac{a_{i+1} - a_i}{t_{i+1} - t_i} \tag{2}$$

This popular method is simple and straightforward. Unfortunately, the resulting crack growth rates show a large amount of scatter. This is because of the interaction between the method of analysis and the real variability in growth rates. For example, during growth, a crack in RPC material may move into a damaged region, blunt excessively while the material near the crack tip is further damaged, and then branch forward into the newly damaged material. Figure 1 shows a crack undergoing this process. If the two data points are both collected when the crack is stationary, a crack speed of zero will be inferred. Overall, however, the crack speeds increase as the relevant crack tip parameter (e.g., $K$) increases. Data analyzed using this method will exhibit large scatter but will give power law parameters similar to polynomial methods. In addition, the actual growth measurements may be more indicative of the actual situation than polynomial methods are, where the crack tip actually does slow or stop. A related method is the modified secant method, which assigns a crack speed to the time at the mid-interval (see eq. 3 below). [4]

$$\left|\frac{da}{dt}\right|_{t=t_i} = \frac{1}{2}\left[\frac{a_i - a_{i-1}}{t_i - t_{i-1}} + \frac{a_{i+1} - a_i}{t_{i+1} - t_i}\right] \tag{3}$$

To reduce scatter and show the correlation of the crack growth rate and fracture parameter more clearly, researchers have used polynomial methods. These include the incremental polynomial method and the total polynomial method. [4] The total polynomial method is the easier of the two to implement, and involves the least squares fitting of a polynomial of an assumed order to the entire set of crack growth vs. time data points for a single test. Most graphing programs do this easily. The order of the polynomial is chosen by examining how well different polynomials fit the data. Adjustments are often necessary (data points near the start and the end of the test are often excluded from the curve fitting procedure). The incremental polynomial is similar in concept, but is applied to consecutive sets of several data points using requirements of first and second derivative continuity at the data points. Regardless of which of these methods is used, the derivatives of the polynomial are used as an approximation to the instantaneous crack growth rates. Figure 6 shows both the secant method and the polynomial method applied to two data sets.
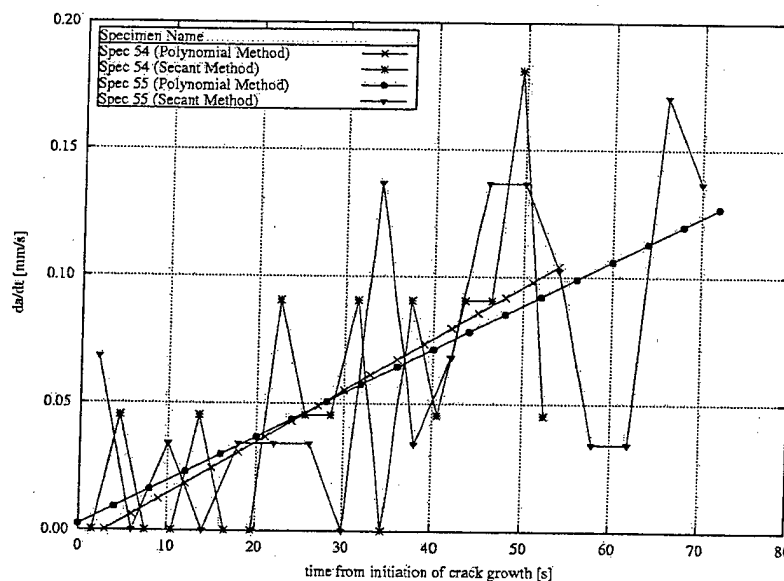


Figure 6: Comparison of Secant and Polynomial Methods Applied to Two Data Sets

## POTENTIAL SOURCES OF ERROR

There are several possible sources of error, summarized here. Already mentioned is the case of the biaxial specimen, where two crack tips are present and specimen-load path misalignments may cause asymmetric crack growth. [3,5]. Another set of potential problems is the accurate assessment of boundary conditions and loads. [3] One of the most prevalent sources of nonuniformity in measurements is the lack of a well-defined crack tip (due to presence of nearby damaged areas), which lends subjectivity to the measurements. In addition, although we know surface measures and interior measurements correlate well in thin specimens, we have not fully verified that this is the case with all specimen geometries. Finally, the use of visual surface measurements sometimes gives parallax problems, especially when viewing through the sight chamber of a pressure vessel (we are sometimes required to test fracture specimens under pressurized conditions). [3]

## SUMMARY

Crack growth and growth rates are measured in laboratory conditions to derive their relationship to fracture parameters so the reliability of solid rocket motors can be assessed. The manufacturing method, heterogeneity of the material, and high ductility contribute to difficulties in the measurement and analysis process. Different specimen geometries and methods for measuring crack size have been used and are described, each having unique advantages and disadvantages. The crack sizes, once determined, are usually converted to growth rates with secant methods or polynomial methods. Potential sources of error include accurate boundary condition assessment, subjectivity in crack length measurement, and problems with maintaining proper crack growth in biaxial specimens.

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